AD-A148 210 IONOSPHERIC AND MAGNETOSPHERIC MODIFICATIONS CAUSED BY VLF WAVES(U) REGIS COLL WESTON MA M C LEE ET AL. 01 JUN 84 AFGL-TR-84-0301 F19628-83-K-0024 1/1

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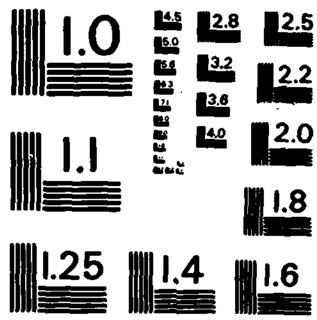

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Unclassified **AD-A148 210** (10)

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a. REPORT SECURITY CLASSIFICATION: Unclassified	1b. RESTRICTIVE MARKINGS: None
2a. SECURITY CLASSIFICATION AUTHORITY: N/A 2b. DECLASSIFICATION/DOWNGRADING SCHEDULE: N/A	3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release, distribution unlimited
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S): AFGL-TR-84-0301
6a. NAME OF PERFORMING ORGANIZATION: Regis College 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION: Air Force Geophysics Laboratory/LIS
6c. ADDRESS (City, State and ZIP Code): 235 Wellesley Street, Weston , Mass. 02193	7b. ADDRESS (City, State and ZIP Code): Hanscom AFB, MA 01731
8a. NAME OF FUNDING/SPONSORING ORGANIZATION: Air Force Geophysics Lab 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: F19628-83-K-0024
8c. ADDRESS (City, State and ZIP Code): Hanscom AFB, MA 01731 John A. Klobuchar	10. SOURCE OF FUNDING NOS.

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT NO.
62101F	4643	09	AB

11. TITLE (Include Security Classification) Ionospheric and magnetospheric modifications caused by VLF waves

12. PERSONAL AUTHOR(S) M.C. Lee; S.P. Kuo*

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Yr., Mo., Day)	15. PAGE COUNT
Scientific - Reprint	FROM ____ TO ____	June 1, 1984	4

16. SUPPLEMENTARY NOTATION *Polytechnic Institute of NY, Long Island Center, Farmingdale,NY 11735
Proceedings of 1984 International Conference on Plasma Physics, Lausanne,Switzerland, June 27 - July 3, 1984

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB. GR.	Thermal filamentation instability; lower hybrid waves; VLF wave injection experiments

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The ionosphere and the magnetosphere may be significantly modified by the injected VLF waves via the thermal filamentation instability and the excitation of lower hybrid waves. -> to pg 1

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS ☐	21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE NUMBER (Include Area Code)	22c. OFFICE SYMBOL
John A. Klobuchar	617-861-3988	AFGL/LIS

DD FORM 1473, 83 APR — EDITION OF 1 JAN 73 IS OBSOLETE. 84 ... 039

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE

AFGL-TR-84-0301

Ionospheric and magnetospheric modifications caused by the injected VLF waves

M.C. Lee

Regis College Research Center, Weston, Mass. 02193, U.S.A.

S.P. Kuo

Polytechnic Institute of New York, Long Island Center,
Farmingdale, N.Y. 11735, U.S.A.

Abstract. The ionosphere and the magnetosphere may be significantly modified by the injected VLF waves via the thermal filamentation instability and the excitation of lower hybrid waves.

1. Introduction

cont In VLF wave injection experiments performed, for example, at Siple, Antarctica, the ground-based transmitters are usually operated in a pulsed-~~wave~~ mode with durations of a few seconds. These VLF wave pulses ~~have been~~ were used to study coherent wave-particle interactions in the magnetosphere such as the wave amplification, the triggering of wave emissions, the induced particle precipitation etc. (see, e.g., Helliwell, 1983). We show in this paper that if the transmitters are operated continuously for a few minutes, significant ionospheric and magnetospheric disturbances can be caused by the following two processes. One is the thermal filamentation of the pump wave and the other one is the excitation of lower hybrid waves.

2. Thermal filamentation of whistlers

Monochromatic VLF waves have been observed to change from linear into circular polarization (i.e., a whistler mode) on their path through the neutral atmosphere and into the ionosphere. If the pump waves are intense enough, the filamentation instability of whistlers can be excited. This instability yeilds a whistler sideband and zero-frequency modes that are associated with the simultaneous excitation of both plasma density fluctuations (δn) and magnetic field fluctuations (δB). The source of these magnetostatic fluctuations stems from the wave-induced quasi-DC electric current due to the electron F x B drift motion under the influence of the differential Ohmic heating force.

Proceedings of 1984 International Conference on Plasma Physics, Lausanne, Switzerland, June 27- July 3, 1984

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The plasma density fluctuations (δn) and the magnetostatic fluctuations (δB) are found to be related as

$$\delta n/n_o \cong [\ 1 + (\nu_e/\gamma)(c^2/\lambda^2 f_p^2)](\delta B/B_o) \qquad (1)$$

where f_p, ν_e, n_o, B_o, γ , and λ are, respectively, the electron plasma frequency, the electron-ion collision frequency, the background plasma density, the earth's magnetic field, the growth rate of the instability, and the scale lengths of the excited modes. It is clear from (1) that significant magnetostatic fluctuations are associated with the excitation of large scale modes.

Although the whistler waves have a broad propagation regime: $|\Omega_e| << \omega_o < |\Omega_e|$, the excitation of the filamentation instability is restricted to whistlers with frequencies (ω_o) satisfying the following condition:

$$1 - \omega_o^2\ \omega_p^2(|\Omega_e| - \omega_o)^{-1}(\omega_p^2 + k^2c^2)^{-1} \quad - k^2c^2|\Omega_e|^{-1}(|\Omega_e| + \omega_o)^{-1}(\omega_o^2 + k^2c^2)^{-1} \quad < \ 0 \qquad (2)$$

where ω_p, $|\Omega_e|$ ($|\Omega_i|$), ω_o , and k are the angular electron plasma frequency, the electron (ion) gyrofrequency, the angular whistler wave frequency, and the wave number of the excited modes, respectively. The inequality (2) demands that $\omega_o > |\Omega_e|/2$ for the excitation of large scale modes. Since $|\Omega_e| \sim 1.4$ MHz (13.6 KHz) in the ionospheric F region (in the magnetosphere at L = 4.0), this result indicates that the thermal filamentation of whistlers can occur in the ionosphere (in the magnetosphere at L = 4.0) when the wave frequencies are within the frequency range: 1.4 MHz > $\omega_o/2\pi$ > 0.7 MHz (13.6 KHz > $\omega_o/2\pi$ > 6.8 KHz).

The threshold of this instability has been found to be

$$|\ e\varepsilon_{th}/mc\ |^2 \sim \ 1.5\ \omega_o^{-1}\ \omega_p^{-2}\ (\omega_o - |\Omega_e|)^3 k^2 v_{ti}^2 (4 - a - ab)^{-1}(1 + b - ab) \qquad (3)$$

where $a = k^2c^2(\omega_o^2 - \Omega_e^2)/\omega_o|\Omega_e|\omega_p^2$, $b = \omega_o\omega_p^2/(\omega_o - |\Omega_e|)(\omega_p^2 + k^2 c^2)$, and v_{ti} is the ion thermal velocity. The threshold fields thus calculated are of the order of a few μv/m (a few mv/m) for exciting modes with tens of kilometers (tens of meters) and larger scales in the magnetosphere at L = 4.0 (in the ionospheric F region), that are achievable whistler wave field intensities with available facilities. However, whistler waves with much higher intensities are required to ensure the excitation of the thermal filamentation instability in the magnetosphere. This is because the growth rate of the instability is rather small if the whistler wave field intensities just barely exceed the threshold fields.

In terms of the threshold (ε_{th}), the growth rate of large scale modes (i.e., $f_p >> c/\lambda$) is given by

$$\gamma_\infty \sim (2\nu_e k v_{ti}/|\Omega_e|)(\varepsilon_o/\varepsilon_{th}) \qquad (4)$$

that turns out to be independent of the scale lengths because as shown in (3), ε_{th} is proportional to k. If $\varepsilon_o/\varepsilon_{th} \sim O(1)$, γ_∞ is of the order of 10^{-5} Hz (10^{-3} Hz) in the magnetosphere at L = 4.0 (in the ionospheric F region). The Siple signals, propagating in the non-ducted whistler mode, have $\varepsilon_o/\varepsilon_{th} \sim O(1)$ in the magnetosphere at L = 4.0. The probability for seeing the Siple signals in the ducted whistler mode is about 20%. The growth rate can be increased by two to three orders of magnitude in the ducted whistler propagation. Therefore, if the Siple transmitter is operated for a few minutes, the thermal filamentation instability can excite in the magnetosphere at L = 4.0 the plasma density fluctuations with scale lengths greater than tens of kilometers. This instability can also be excited in the ionospheric F region by the MF waves with frequencies close to but less than the local electron gyrofrequency.

3. Excitation of lower hybrid waves

The injected VLF waves can interact directly with the ionosphere through the excitation of lower hybrid waves and a field-aligned purely growing mode. This instability can be excited in a broad whistler frequency range in two domains. They are Domain 1: $\omega_{LH}[1+(M/m)(v_t^2/c^2)(\omega_p^2/\Omega_e^2)]^{1/2} < \omega_o < \omega_{pi}$ for the non-oscillatory beating current to be the dominant nonlinear effect, and Domain 2: $\omega_{pi} < \omega_o << |\Omega_e|$ for the thermal pressure force to be the dominant nonlinear effect, where ω_{LH} defined by $\omega_{pi}/(1+\omega_p^2/\Omega_e^2)^{1/2}$ is the lower hybrid resonance frequency; $\omega_{pi}(\omega_p)$, $|\Omega_e|$, v_t , and (M/m) are the ion (electron) plasma frequency, the electron gyrofrequency, the electron thermal velocity, and the ratio of ion to electron masses, respectively.

The optimum threshold field for the instability is found to be

$E_m \sim 1.2\,(m/e)\nu_e v_t |\eta|^{1/2}$ in frequency domain 1 and $E_m \sim 0.86(k^2 v_t^3/\Omega_e)(m/e)[1 + (1 + 4\Omega_e^2\nu_e^2\eta^2/k_s^2 v_t^2)^{1/2}]^{1/2}/|\eta|^{1/2}$ in frequency domain 2, where ν_e and k_s are the electron-ion collision frequency and the wave number of the excited field-aligned mode, respectively; $\eta = [1 + (M/m)(k_o/k_s)^2]/[1 - (M/m)(K_o/k_s)^2(\Omega_e/\omega_p)^2]$, where k_o/k_s is the ratio of the perpendicular to the parallel scale lengths of the excited lower hybrid waves.

The growth rate of the instability has the following expressions, $\gamma \sim 0.5(\nu_e k_s^2 v_t{}^2/\Omega_e^2)(E_R^2 - 1)$ for $E_R^2 \ll 10$ and $\gamma \sim 1.4(\nu_e k_s^2 v_t{}^2/\Omega_e^2)E_R$ for $E_R{}^2 \gg 10$, where E_R is the ratio of the whistler field intensity (E_o) to the optimum threshold field intensity (E_m) of the instability. Since $\omega_{LH} \sim 6$ KHz in the ionosphere, the whistler wave frequencies have to be greater than 6 KHz for the excitation of lower hybrid waves. The threshold field has been estimated to be about 1 mv/v. If $E_R \sim 0(10)$, the instability with dominant scale lengths near 10 meters can be excited within a few seconds in the ionosphere. By contrast, kilometer-scale lower hybrid waves can be excited in the magnetosphere at L = 4.0 with much lower threshold field ($\sim$ a few μv/m). The growth rate is, however, rather small for non-ducted whistler modes, whose $E_R \sim 0(1)$. Whereas, the ducted whistler modes can excite the instability with growth rates as large as 10^{-2} Hz. In other words, lower hybrid waves can be produced by ducted whistler waves in the magnetosphere within a few minutes. Electron precipitation is the ionospheric effects expected from the excitation of lower hybrid waves. Indeed, airglow effects have been observed in the Russian Juliana program (Chmyrev et al., 1976) to be associated with the VLF transmitter cycle.

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Acknowledgements. This work was supproted by AFGL contract F19628-83-K-0024 at Regis College Research Center and jointly in part by NSF grant ATM-8315322 and in part by the Air Force Office of Scientific Research grant AFOSR-83-0001 at Polytechnic Institute of New York.

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